

Photoemission Electron Microscope Directly Views Spin Alignment

Researchers from the Advanced Light Source (ALS), IBM, and Arizona State University have taken a major step toward the solution of a long-standing problem in magnetic multilayers: identifying the mechanism of directional coupling between spins in an antiferromagnet and those in an adjacent ferromagnet. Known as exchange bias, this coupling plays a key role in magnetic devices based on the giant magnetoresistance (GMR) effect. Using the photoemission electron microscope at the ALS (PEEM2), the group obtained x-ray magnetic dichroism images that revealed the magnetic structure on both sides of the interface between a thin layer of ferromagnetic cobalt grown on antiferromagnetic lanthanum iron oxide (LaFeO_3), as well as local remanent hysteresis loops for individual ferromagnetic domains. The experiments may lead to a definitive understanding of the elusive mechanism of exchange biasing.

Devices based on the GMR effect consist of a sandwich of a nonmagnetic metal layer a few atoms thick between two thin ferromagnetic layers, the bottom layer of which is grown on top of an antiferromagnetic substrate. An external magnetic field can switch the magnetization direction of the outer ferromagnetic layer, but the magnetization of the layer grown on the antiferromagnet is pinned in one position by exchange biasing. The flipping of the magnetization orientation of the two ferromagnetic layers from parallel to antiparallel changes the resistance state of the material from low to high. Although exchange bias is important to a multibillion-dollar industry, the basic physics is not well understood, largely because of the lack of techniques capable of studying in detail the magnetic moments near interfaces.

To attack this problem, the ALS/IBM/Arizona State "PEEM team" combined polarized synchrotron radiation from the ALS with the new PEEM2 microscope

with a spatial resolution as good as 20 nm. For some years, experimenters have been able to image ferromagnetic domains in thin layers by means of x-ray magnetic circular dichroism (XMCD), in which the absorption of circularly polarized x rays depends on the relative orientation of the polarization and the magnetization of the domain, thereby providing magnetic contrast. Antiferromagnetic materials have typically posed a bigger problem because the alternating orientations of the spins at each atom result in no net magnetic moment. Recently, the team showed that use of x-ray linear magnetic dichroism (XMLD) could be employed to image antiferromagnetic domains in LaFeO_3 . Here the contrast arises at an absorption edge that splits into two peaks (multiplets) with heights that depend in opposite ways on the angle between the x-ray polarization and the antiferromagnetic axis.

Putting it all together, the team studied a sample comprising a thin

(1.2-nm) cobalt layer on a 40-nm thick layer of LaFeO_3 . Owing to the thinness of the cobalt, electrons emitted from the underlying layer were able to escape, and the magnetic structure on both sides of the interface could be imaged. XMLD images made at the split L_3 edge of iron resulted in a pattern of dark and light areas, according to the orientation of the antiferromagnetic axis. XMCD images made at the $L_{3,2}$ edge of cobalt resulted in a pattern highly correlated with that from LaFeO_3 . Horizontally oriented domains, which showed up as light areas in the LaFeO_3 , appear as gray areas in the cobalt. Vertically oriented domains, which showed up as dark areas in LaFeO_3 , appear either dark or light in the cobalt, depending upon spin orientation (up or down, respectively). These results and the local remanent hysteresis loops recorded in individual ferromagnetic domains imply that the alignment of the ferromagnetic spins is determined, domain by domain, by the spin orientation in the antiferromagnetic layer. ■

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F. Nolting, A. Scholl, J. Stöhr, J.W. Seo, J. Fompeyrine, H. Siegwart, J.-P. Loquet, S. Anders, J. Lüning, E.E. Fullerton, M.F. Toney, M.R. Scheinfein, and H.A. Padmore, "Direct observation of the alignment of ferromagnetic spins by antiferromagnetic spins," *Nature* **405**, 767 (2000). A. Scholl, J. Stöhr, J. Lüning, J.W. Seo, J. Fompeyrine, H. Siegwart, J.-P. Loquet, F. Nolting, S. Anders, E.E. Fullerton, M.R. Scheinfein, and H.A. Padmore, "Observation of antiferromagnetic domains in epitaxial thin films," *Science* **287**, 1014 (2000).



IMAGING EXCHANGE BIAS IN MAGNETIC LAYERS

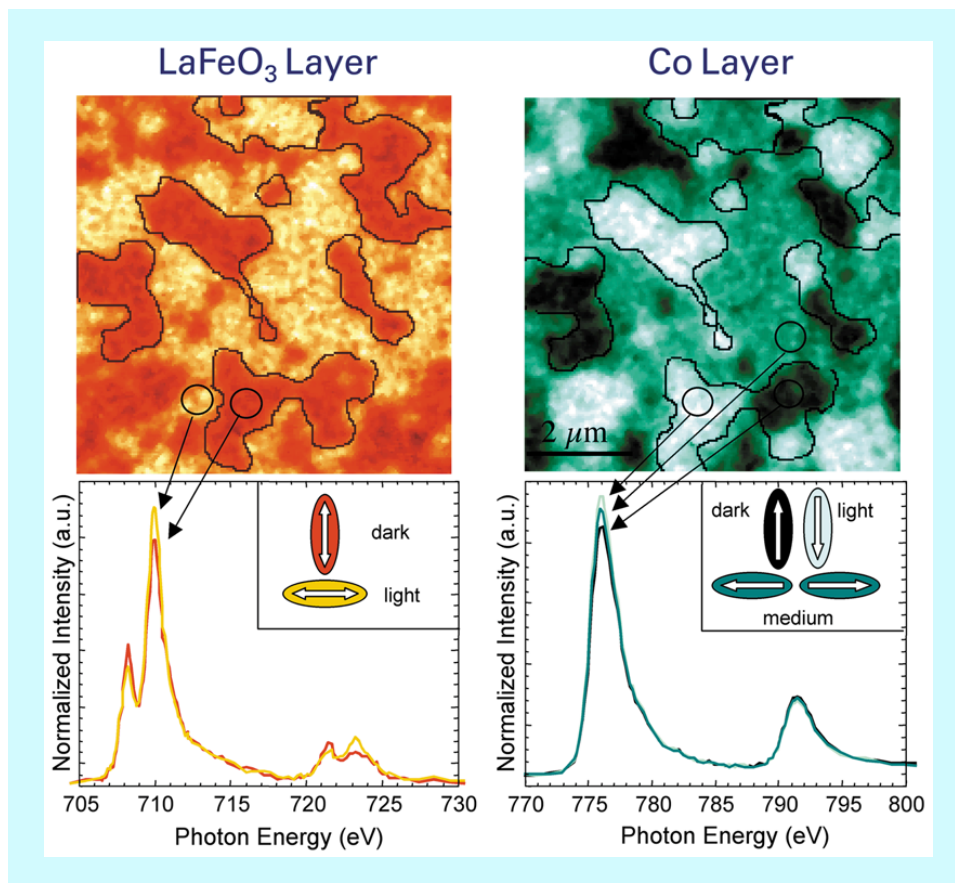


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- **Exchange bias in magnetic nanostructures**
 - *An interfacial effect discovered in 1956*
 - *Spins in antiferromagnetic (AFM) layer align spins in adjacent ferromagnetic (FM) layer*
 - *How exchange bias works still not understood*
- **A key mechanism in new giant magnetoresistance (GMR) devices**
 - *Sandwich comprising (bottom to top) AFM/FM/nonmagnetic/FM layers*
 - *Exchange bias pins magnetization of the bottom FM layer to that of the AFM layer*
 - *Provides a reference as an external field switches magnetization of the top FM layer*
 - *Resistance depends on relative magnetization orientation of the two FM layers*
- **Photoemission electron microscope views magnetic structure**
 - *X-ray magnetic circular dichroism images domains in the FM layer*
 - *X-ray magnetic linear dichroism images domains in the AFM layer*
 - *PEEM2 at the ALS has a resolution as good as 20 nm*
- **Co ferromagnetic layer of LaFeO₃ antiferromagnetic layer**
 - *Images imply alignment of FM spins is determined by spin direction of AFM layer*
 - *Remanent hysteresis loops for individual FM domains show local exchange bias*
 - *Opens door to a definitive understanding of exchange bias mechanism*

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Linear dichroism at Fe L edge images AFM domains (left). Circular dichroism at Co L edge images FM domains (right). Comparison of images shows that the Co domains align with the AFM domains (light and dark regions inside outlined areas).